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REVIEW OF TIME SCALES

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ABSTRACT

The basic time scales are presented: International Atomic Time, Universal Time, and Universal Time (Coordinated). These scales must be maintained in order to satisfy specific requirements. It is shown how they are obtained and made available at a very high level of precision.

INTRODUCTION

Until 1956, the unit of time, the second, was defined as a fraction of the mean solar day. However, the duration of the mean solar day was found to be variable, and a better definition, made possible by the progress of physics, was given in 1967, when the second was defined to be a certain number of periods corresponding to a transition of the cesium atom. The relative accuracy of the realization of the second was thus improved from 1×10^{-7} to 1×10^{-13} (1974). In the meantime, from 1956 to 1967, the second was defined to be a certain fraction of the year, more stable than the day; but this second was so difficult to implement, that its quasi-unique use was to calibrate the atomic second.

The situation of the unit of time is clear: only the last defined unit is used by the physicists. Nevertheless, none of the time scales associated with the three definitions of the unit could be abandoned, because they satisfy specific requirements. We thus have three basic time scales in simultaneous existence: Universal Time, UT1 (often called Greenwich Mean Time), based on the rotation of the Earth; the Ephemeris Time ET, based on the motion of the Earth around the Sun; and the International Atomic Time TAI (fig. 1). In the following, we will not discuss the problems of Ephemeris Time, because ET is in limited use and is being redefined; we will concentrate on UT1 and TAI.

The origin of TAI was arbitrarily chosen so that the TAI and UT1 readings on January 1st 1958 were the same. But they do not run at the same rate, and now, in December 1974, they differ by more than 13s; even less sophisticated users cannot ignore this difference. As we shall see, some users need UT1, others TAI. In order to avoid the risk of confusion which would arise from the dissemination of two time scales, it was agreed that the time signals will follow

a unique compromise time scale, designated Universal Time (Coordinated), UTC. The definition of UTC is very simple: it differs from TAI by an integral number of seconds, this integral number being changed by one unit, when necessary, in order to maintain $|UT1-UTC| < 0.9$ s. The International Radio Consultative Committee gave precise rules for the implementation of UTC, and also defined a simple code used in time signal emissions which enables the field user to obtain UT1 immediately to ± 0.1 s (1).

The problems of the determination and of the dissemination of UTC are the same as for TAI and will be discussed together in what follows.

Figure 2 shows the relative behaviour of UT1, TAI and UTC.

INTERNATIONAL ATOMIC TIME AND UNIVERSAL TIME (COORDINATED)

Their formation

As soon as the frequency of crystal clocks could be calibrated in real time by a cesium frequency standard, at the National Physical Laboratory in 1955 (2) astronomers began to form a time reference suitable for the study of the rotation of the Earth. When other cesium standards appeared, data were combined in order to increase the stability. Several atomic time scales were thus developed in national and international institutions, differing slightly in rate and phase. As the use of atomic time extended to many other fields of activity, it was desirable to agree on a unique time reference. This was done in October 1971, by a decision of the 14th General Conference of Weights and Measures, which defined International Atomic Time TAI as the time reference maintained by the Bureau International de l'Heure (BIH) from the readings of atomic clocks.

TAI is presently based on the data of about 60 commercial cesium clocks, located in 15 laboratories and observatories of North America and Europe. These clocks are daily intercompared by the use of LORAN-C pulses, with an accuracy of a few 0.1 μs. Their data are combined by an algorithm which intends to 1) minimize the noise due to introductions and removals of clocks, 2) ensure the long term stability (over years) by an appropriate weighting procedure (3). The random noise in TAI for a sampling time τ over 2 months is a flicker frequency modulation (4) with σ (2, τ = 1 year) of the order of 0.5×10^{-13} . For smaller values of τ the main source of uncertainty is the LORAN-C link across the Atlantic Ocean, which introduces fluctuations extending over a few weeks, with an amplitude reaching 1 μs (5). Some small non-random errors of TAI were revealed by reference to the recently developed primary frequency standards; the frequency of TAI should be corrected by about $-1 \times 10^{-12} + 1 \times 10^{-13}$ (t - 1973), t in years, the amount of the frequency drift being very uncertain. In the near future, these non-random errors will be reduced and the long term stability

will be improved by the use of the data of primary standards, after convenient filtering (6). Other improvements are expected from the elimination of some systematic errors in the LORAN-C time transfers and from the extension of the coverage of precisely synchronized chains. With the present coverage, sets of good clocks, especially in Japan and Australia, are not included.

TAI is the best measure of time for long term studies and therefore is to be used in dynamical studies of the motions of celestial bodies, both natural and artificial. It also acts as a frequency memory which enables one to compare the frequencies of oscillators separated in space and time, and it provides users with a means of referring frequencies to any of the primary frequency standards.

As previously said, TAI is not disseminated; the time signals and the master clocks of laboratories follow UTC, which is therefore the common worldwide reference by which all events must be dated. Of course, according to its definition, UTC is produced by the BIH simultaneously with TAI.

Dating of events in UTC

UTC (and TAI) is established in retrospect as the result of computations, and no real clock runs exactly on UTC.

The first step for dating an event in UTC is to find some real reference clocks giving access to UTC. For those laboratories of which the clocks enter into the determination of UTC and TAI, the outputs of the BIH algorithm are corrections to be added to the readings of these clocks to get UTC and TAI. Any such clock is therefore a local time reference, but for the purposes of simplification one per laboratory is generally selected which produces the local approximation to UTC, designated UTC(i) for laboratory (i). The tables published monthly by the BIH give the values of UTC-UTC(i) every 10 days, with uncertainties of a few 0.1 μs, but in arrears by 1 to 2 months (fig. 3). It is, however, possible in well equipped laboratories to extrapolate UTC-UTC(i) up to the present with errors less than ± 1 μs and even, in some cases, to steer a clock so that it remains close to UTC. For instance, the USNO master clock did not deviate by more than 1 μs from UTC from 1 January 1973 to 21 July 1974. Within these limits of ± 1 μs, UTC is therefore immediately available.

For the observer, the problem now is to find a time link with one of the standards UTC(i). It is beyond the scope of this paper to present the various techniques which are available. But it is worthwhile to note that for the larger part of the globe, microsecond accuracy can be reached by clock transportation only. When millisecond accuracy is sufficient, UTC is directly available by standard time signal emissions.

It must be emphasized that, at the present level of precision, international co-operation in matters of atomic time scale depends entirely on the LORAN-C time transfers with the help of occasional clock transportations. Long distance time intercomparisons are less amenable to future improvements than the clocks themselves. Any improvement of the LORAN-C time transfers or the development of more precise methods will have a direct impact on the quality of TAI and UTC and on their dissemination.

UNIVERSAL TIME

Under the general designation "Universal Time," there are several time scales, close to each other and related to the rotation of the Earth. Only the UT1 scale is important for the general user; it expresses a measure of the angular position of the Earth around its instantaneous axis of rotation.

Although it is questionable to a logical mind to consider UT1 as a time scale, it is practical and convenient to do so. Since the rotation of the Earth is not uniform, the difference of times assigned to the same event in the UT1 and TAI scales will vary with the calendar date. But as this difference, expressed by UT1-TAI, is slowly varying (by about 3 ms per day, presently), it is sufficient to have tables giving UT1-TAI and UT1-UTC. The reception of time signals in the UTC system and the use of these tables give easy access to UT1, but not in real time; and for UT1, no good extrapolation is possible.

There are two main reasons why UT1-TAI must be known as precisely as possible, simultaneously with the two coordinates of the terrestrial poles, which are moving on the Earth's surface: the geophysical applications, and the geometrical ones.

The geophysical processes which give rise to the irregularities of the Earth's rotation and therefore of UT1-TAI are not yet fully known. The motion of the atmosphere plays an important role, especially for short-term irregularities, but contributions are also due to tidal fiction, motions in the oceans and in the fluid core of the Earth. UT1-TAI cannot be predicted, and precise experimental measurements are needed for a better knowledge of the perturbing forces.

The geometrical applications are related to the tracking of celestial bodies. Most of the observations are made from the rotating Earth and are referred to a terrestrial frame of reference. It is therefore necessary to know all the parameters of the Earth's rotation in space. One of them is UT1. For instance, UT1 is needed for reducing meridian observations of stars and some radiointerferometric measurements. But the most striking application is to the navigation of interplanetary space probes. At a distance equal to that of the Sun from the Earth, 1 ms error in UT1 (which is the present level of uncertainty) corresponds to about a 10 km error in position, which is far from being negligible.

The only technique presently used for determining UT1 on a routine basis is the observation of star transits across a reference circle by about 60 astronomical instruments: photographic zenith tubes, astrolabes, and meridian transit instruments. The data of these instruments are combined by the BIH, which publishes monthly tables giving UT1-UTC and UT1-TAI every five days. The short term stability of these results is given by the square root of the Allan variance σ $(2, \tau = 5 \text{ days}) = 1.5$ ms. But the errors are not white noise; besides periodic annual errors with a possible amplitude of 2 to 3 ms, the noise seems to lie between white and flicker phase modulation (fig. 4).

Improvements in the measure of UT1 can be expected from new astronomical instruments such as the large PZT of the U.S. Naval Observatory and the photoelectric astrolabe developed in France. However, classical methods are limited by the turbulence of the atmosphere. New techniques such as satellite observations and lunar laser ranging either alone or in association with classical astrometry are promising. Long baseline radiointerferometry could reduce the errors by a factor 10 or even more. But it must be kept in mind that the Earth's rotation must be monitored continuously. The classical methods, which are not so expensive as the new ones, will have to be used until it is proved that the new ones provide better results on a continuous basis.

Another improvement from an operational point of view would be to reduce the delay in providing UT1 to a given level of uncertainty.

In some cases UT1 should be available immediately, as, for instance, for the navigation of space probes. Presently, the delay of 1 to 2 months necessary to reach 1 ms accuracy is due to the need of having a two-sided smoothing for reducing the effect of accidental errors; the shortening of this delay also requires more precise observations.

CONCLUSION

In matters of time scales, international cooperation is important both for a better evaluation of the scales and for ensuring their worldwide acceptance. I will not enter into the political intricacies of the official organizations dealing with time. It is often difficult to say which organization is responsible for what. But the international arrangements work surprisingly well. The BIH, which is the executive body acting under the sponsorship of these organizations, does not receive contradictory instructions.

The BIH, formerly in charge of publishing the times of emission of signals in UT1, extended its activities to atomic time and to the coordination of clocks in the UTC system in recent years. Well automated data handling has enabled us

to cope with an increase of work in spite of reductions in the number of our staff and in our grants.

However, nothing could have been accomplished without the constant support of all the laboratories and observatories which concur to produce the final data. Here is the appropriate place to thank the U.S. organizations which are especially helpful: the National Bureau of Standards, the U.S. Coast Guard, and the U.S. Naval Observatory.

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Definition	Unit of time: Validity of the definition	Unit of time: Relative Accuracy of the realized unit of time	Associated Time Scales
1/86 400 mean solar day	⟶ 1956	1×10^{-7}	Universal Time UT1
1/31 556 925.9747 tropical year (for 1900 Jan. 0)	1956-1967	5×10^{-9}	Ephemeris Time ET
9 192 631 770 periods correspon-ding to a transition of the cesium atom	1967 ⟶	1×10^{-13}	International Atomic Time TAI

Figure 1.

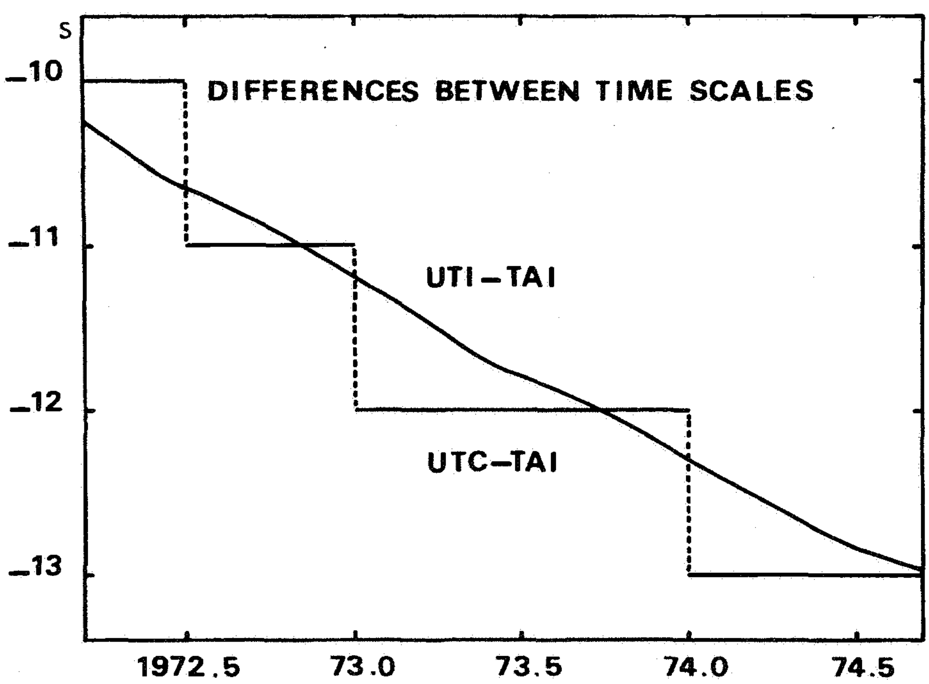


Figure 2.

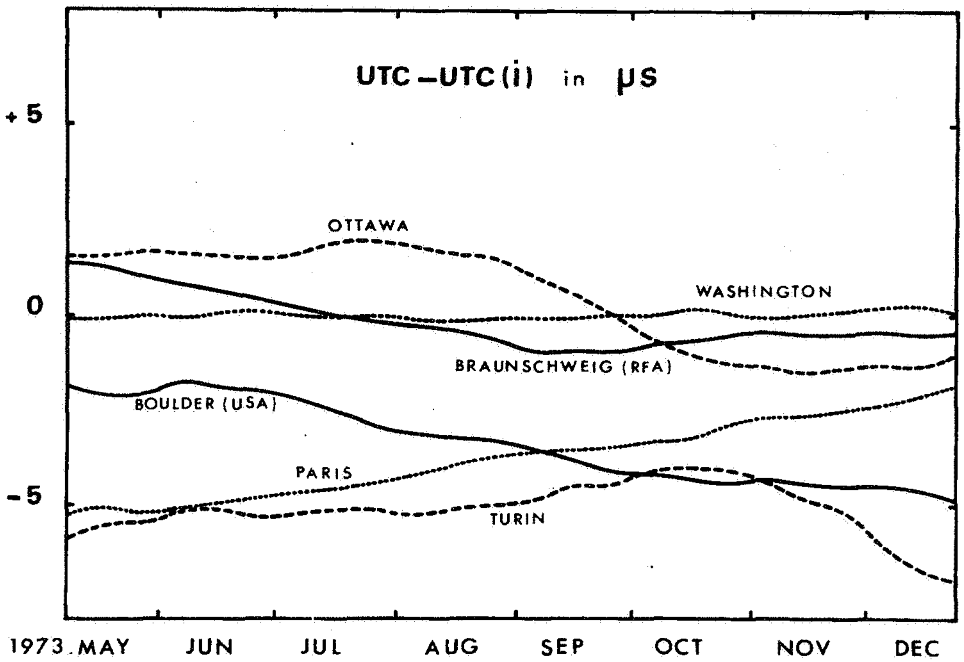
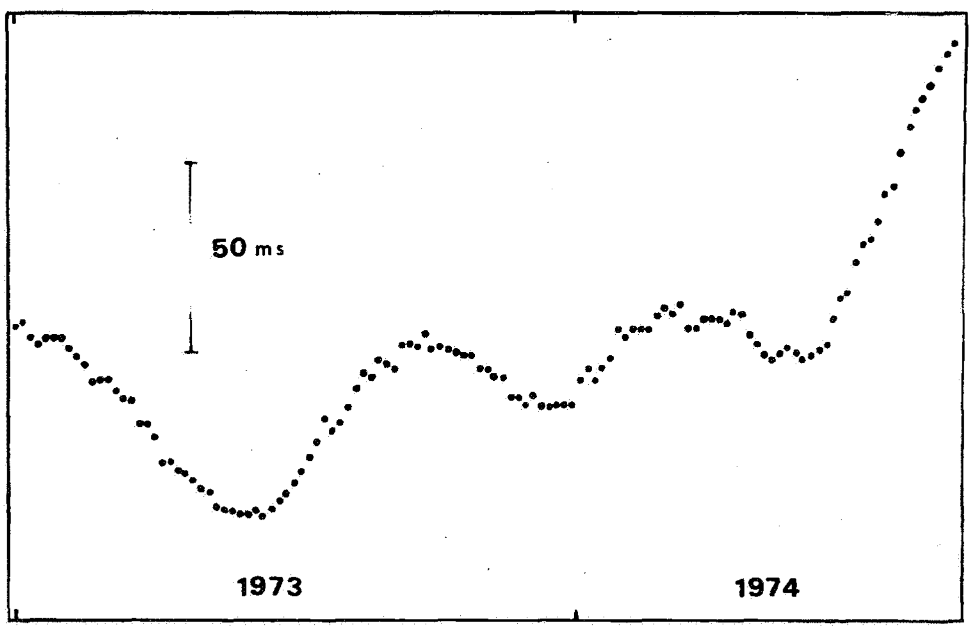


Figure 3.



UT1 — UNIFORM TIME

Figure 4.